Slag Tap Firing System
for a Low-Emission Boiler

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R. Beittel (508-792-4811)
T. Ake (508-792-4819)
E. Reicker (508-792-4808)
DB Riley, Inc.
Worcester, MA 01610

Introduction

DB Riley, Inc., is leading one of three industry teams in a DOE-supported program to develop a new generation of coal-fired Low-Emission Boiler Systems (LEBS). The project team consists of DB Riley, Inc., Sargent & Lundy LLC, Thermo Power Corporation, the University of Utah, and Reaction Engineering International.

The overall objective is to develop relatively near term technologies to produce Low-Emission coal-fired Boiler Systems (LEBS) ready for full scale commercial generating units (CGU) by the end of the decade. The project goal is to develop a system which will meet emission limits of 0.1 lbs/million Btu NO_x, 0.1 lbs/million Btu SO_2, and 0.01 lbs/million Btu for particulate. Additional objectives include improved ash disposability, reduced waste generation, reduced toxic substance emission, and increased efficiency, with a goal of approaching or exceeding 42% net plant efficiency (HHV basis).

The team has developed a LEBS capable of meeting all emission and performance goals. The system includes a supercritical boiler fired with a low-NOx, slag-tap firing system, a regenerable desulfurization system with de-NO_x capability, advanced low-temperature heat recovery, and particulate removal. The firing and de-SO_x/NO_x subsystems have been the focus of testing and development efforts within this program to date.

After presenting a review of the LEBS concept, the overall test program, and the Proof-of-Concept (POC) Test Facility, this paper will describe in more detail the results of the 30 MW_t (nominally 10-MW_e equivalent) firing system tests. These tests have demonstrated that application of an advanced low-NOx burner, in combination with either air staging alone, or with coal reburning (staged fuel), can reduce NO_x to less than 0.2 lbs/million Btu in a U-fired slag tap system. Low NO_x slag tap operation was demonstrated with a high-sulfur, midwestern coal, and with a medium sulfur, eastern coal.

LEBS CGU

The DB Riley team has developed a Commercial Generating Unit (CGU) design incorporating an advanced slagging firing system, supercritical steam cycle, regenerable flue gas cleanup, and low-temperature heat recovery. This approach, in addition to meeting all emission and performance goals, eliminates flyash and scrubber solid waste streams.

The LEBS CGU design has significant benefits for local and global environmental quality:

- The vitreous granulate produced by the slag tap boiler (in place of fly ash) is non-leachable, dust free, and has a significant value as a salable by-product, eliminating the need for landfill.
- Sulfur in the coal can be converted to one of several byproducts, including ammonium sulfate, a fertilizer which can have significant value in many parts of the world.
- Nitrogen oxide can be controlled by in-furnace technology, reducing or eliminating reagent and catalyst required for post-combustion cleanup.
- Less CO_2 will be emitted: High cycle efficiencies will result in less CO_2 emissions per MW generated; regenerable SO_2 control eliminates the consumption of limestone and associated release of CO_2

The system concept is shown in Figure 1.

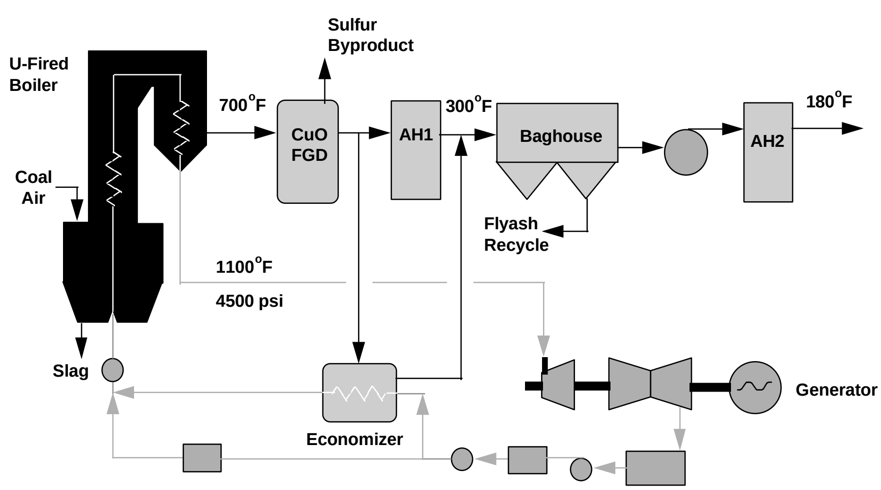

Figure 1. LEBS Commercial Generating Unit Concept

Firing System. Granulated slag from slagging, or "wet" firing systems typically has a specific volume of one-half to one-third that of flyash, and is essentially inert in leaching characteristic tests. These factors make it both more marketable than ash as a byproduct, and, if necessary, more economical to landfill. One of the achievements of this program was to develop a slagging firing system compatible with the NO_x emissions targets.

Combustion NO_x control is achieved through the application of low-NO_x burners, air staging, and coal reburning technology to the U-fired boiler design. Based on successful testing in Phase II, combustion control will reduce NO_x leaving the boiler to less than 0.2 lbs/MBtu. Through the use of flyash reinjection, all of the coal ash can be removed as vitrified slag, and high overall carbon conversion efficiencies are also assured.

Boiler and Steam Cycle. The LEBS Commercial Generating Unit (CGU) design incorporates a supercritical steam cycle with main steam conditions of 4500 psi and 1100°F, and two reheats, each at 1100°F. A low temperature economizer, heating a portion of the feedwater in parallel with the first combustion air heater, reduces extraction steam consumption in the feedwater train. This allows the flue gas to be cooled to 180°F in a second air heater, with high conversion efficiency of this low level heat. The net efficiency of the CGU design is 42.2% (higher heating value (HHV) basis, 2.0 in. Hg turbine backpressure). Care is required in comparing this efficiency to other cycles. Selection of a lower heating value basis would typically add 2 to 4 points in nominal efficiency; selection of design turbine backpressure (i.e., heat sink temperature) can change the efficiency by several points.

The 4500 psi/1100/1100/1100°F cycle is proposed as a commercial system for the near term, and does not represent a maximum efficiency for the Rankine cycle. Over the longer term, continued advances in materials and boiler design are expected to yield steam plant efficiencies comparable to competing, higher risk cycles under development.

Post Combustion Emissions Control. The flue gas leaving the boiler economizer at about 750°F is desulfurized in a moving bed adsorber. The sorbent, alumina impregnated with copper oxide, is regenerated in a separate reactor. The primary function of the adsorber is to remove sulfur dioxide from the flue gas. The copper oxide/copper sulfate bed also acts as a selective catalyst for NO_x reduction, and NO_x may be reduced to very low levels without significant added capital cost by the addition of an ammonia injection system. Additional process advantages include essentially complete removal of SO_3, partial removal of particulate, similar adsorption and regeneration temperatures, low parasitic power, and flexibility for sulfur, acid, or fertilizer byproduct.

The desulfurized flue gas is cleaned of particulate in a pulse jet fabric filter. The dust and acid-free gas is then further cooled in a second air heater, increasing plant efficiency. As an option for reduction of toxic substances, the fabric filter can be configured after the second air heater. Filtration of the particulate at this low temperature increases the removal of volatile species, and removal can be enhanced by addition of sorbents such as lime or active coke.

Phase II Test Program

The Phase II development and testing activities focused on the low-NO_x slag tap firing system and the copper oxide regenerable flue gas cleanup process. Both systems are central to the emissions and waste minimization goals of the project, but lacked an adequate design base for implementation at POC Facility scale. In contrast, the design base and risks for the low temperature heat recovery system were judged to be adequate for trial in the POC Facility. The design base for the selected supercritical cycle was judged to be adequate, particularly in view of concurrent engineering studies and materials development programs elsewhere.

The following activities were directed toward addressing the design deficiencies in the firing and emission control subsystems, in order to provide a sound basis for the design of the POC Test Facility:

- A 30 MW_t (100 MBtu/hr) U-fired slagging test furnace was designed, constructed and tested at the DB Riley Research Center in Worcester, Massachusetts. The key design deficiency investigated was whether NOx emissions could be controlled in a system representative of a full scale, slag tap steam generator. While a number of slag-tap firing technologies are proven in high capacity steam generator service, none had approached the in-furnace NO_x control goal we had set, comparable to the performance achievable with state-of-the-art dry firing systems.

- Coal reburn parametric tests were performed at the University of Utah's new 4 MW_t (15 million Btu/hr) L1500 test furnace. These tests were aimed at supporting the 30 MW_t tests by exploring selected variables in a smaller, more flexible system.

- U-fired combustion systems were simulated at three scales: 30 MW_t test furnace; 40-80 MW_e POC furnace and 300 MW_e commercial scale using reacting computational fluid dynamic models. These models will be an essential tool in applying the Phase II results to POC Facility design, and subsequently to the design of larger commercial generating units.

- Bench scale studies of copper oxide sorbent reactivity were conducted, and process models were developed. These activities were directed at understanding the fundamental adsorption and regeneration chemistry, developing improved and more economical sorbents, and developing the design tools necessary for process optimization and scale up.

- A 1 MW_t pilot scale regenerable copper oxide process was designed, constructed and tested at the Illinois Coal Development Park located in Carbondale, Illinois. The objective of this facility was to provide operating experience and performance data for the moving bed configuration, at a larger scale than previously available (The FETC Life Cycle Test Facility), and, to test a number of important design concepts aimed at improving the performance and economics.

Summary Results of the Test Program

Firing System. The test program demonstrated that a firing system consisting of an advanced low NO_x burner, with either air staging or coal reburning, can meet the LEBS firing system goal of 0.2 lbs/MBtu. The low NO_x CCV® II burner gave dramatically lower emissions than existing U-fired boilers, even without staging or reburning. With reburning or staging, it achieved the project goal without the need to operate at very rich burner stoichiometries. The UFTF results were validated by testing with a burner modified to simulate the burners in an existing boiler; in those tests, both the trends and the absolute values of NO_x matched those from the full scale U-fired boiler. The results of the firing system development and testing show that the firing system is ready to proceed to the POC scale at 40 to 80 MW_e.

Post-Combustion Control. Comprehensive reaction and process models were developed for both the adsorber and regenerator. A lower cost sorbent production method was developed. The subsystem test program at the 1 MW_t pilot scale copper oxide flue gas treatment facility validated key process design features, and identified areas requiring further development and testing. Continued pilot scale testing is planned, in order to improve the performance of the regenerator and demonstrate continuous operation at greater than 98% SO_2 removal. A 10 MW_e equivalent Single Module Test Facility is planned as the next level of scale up.

Proof-of-Concept Test Facility

Two sites were evaluated in Phase III for the POC Test Facility: Greenfield Option, an 80 MW_e mine mouth power plant at the Turris Mine, Elkhart, Illinois; Repowering Option, a 40 MW_e equivalent cogenerating steam plant, at the Savannah River Site steam generation plant near Aiken, South Carolina. Both projects would provide a LEBS reference plant which would provide significant benefits in moving to commercialization of the technology. Each of the POC site alternatives is capable of demonstrating the primary and some secondary (e.g. nonleachable vitrified ash) LEBS emission goals. Both POC options included:

- A full scale, U-fired low-NO_x slag tap boiler, designed for continuous operation and capable of meeting the service life and availability demands for commercial operation following the completion of the test program. The firing system and boiler will provide a commercial scale reference plant for this technology.
- A 10 MW_e equivalent copper oxide Single Module Test Facility (SMTF), designed to test a single, commercial scale adsorber module in continuous operation in an operating power plant. The SMTF includes the all equipment and processes which are required to develop the technology base to allow the copper oxide process to be offered commercially as part of a low emission boiler system. A full stream copper oxide plant is an option, contingent on progression through the SMTF scale prior to construction of the steam generating plant.

30 MW_t Firing System Test Program

The LEBS firing system design integrates the latest low-NO_x burners with advanced air staging and reburning technology to reduce the U-fired furnace NO_x emissions to the 0.2 lb/million Btu level. In the basic U-fired design, swirl burners fire downward into a refractory lined combustion chamber. Slag is collected and tapped at the bottom of the chamber where the gases turn upward through a slag screen into the radiant furnace. The firing system concept, as applied in the 30 MW_t U-fired test facility, is shown in Figure 2.

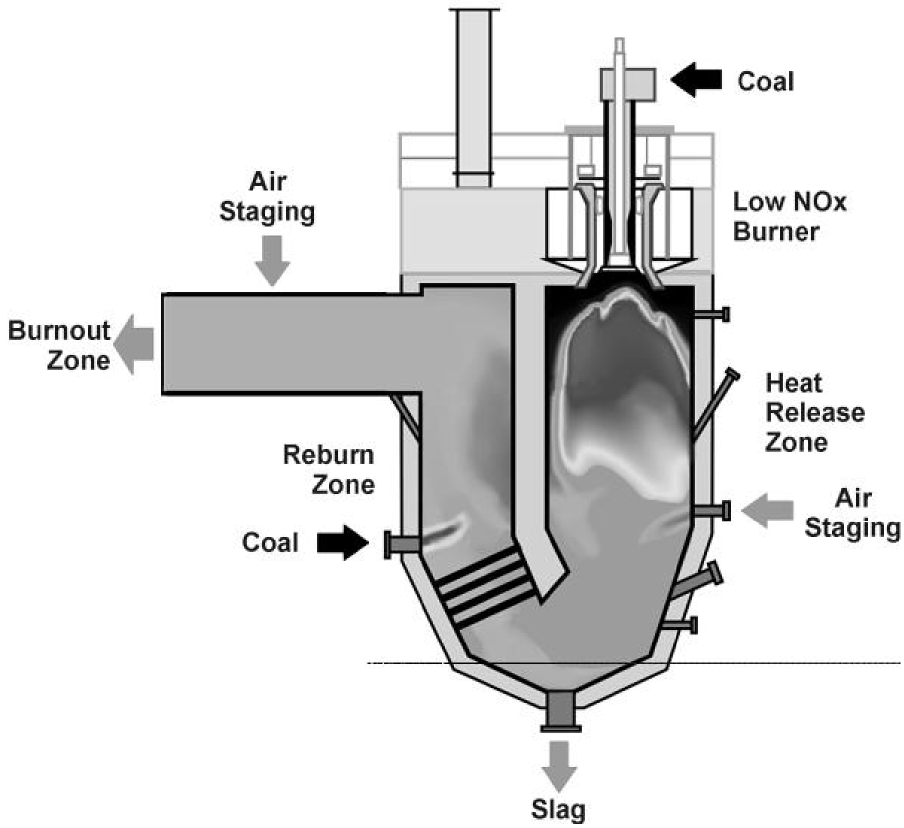

Figure 2. 30 MW_t U-fired Test Facility

The test facility design incorporates a single Riley CCV® II low-NO_x burner in a 9' x 9' x 25' combustion chamber with one staging air level located in the chamber. Reburn coal injection ports are available both before and after the slag screen. Additional staging air ports are located in the vertical upflow section after the slag screen and in the horizontal breeching sections.

The primary objective of the test program was to develop a low-NO_x, slag-tap firing system. However, in addition to low-NO_x production, the firing system must satisfy other demands. Key among these, for either dry ash or slag tap systems, are flame stability, high combustion efficiency, fuel flexibility, and operating characteristics consistent with reliable steam production and protection of the boiler tubes. A further requirement for slag-tap systems is that the combustion chamber temperature be sufficiently high to allow continuous withdrawal of molten ash. These requirements place significant restrictions on the parameters used to minimize NO_x production. This section also describes findings related to these essential U-fired furnace performance requirements, as well as a validation of UFTF results by comparison to full scale units.

Test Program Overview

The majority of parametric tests were completed with Illinois No. 5 coal, a high-sulfur, HV Bituminous C produced at the Turris Mine in Elkhart, Illinois. The Turris Mine is a potential greenfield POC facility host site. This fuel is identified as “Turris coal” in the results sections.

Selected conditions were tested with a medium sulfur, HV Bituminous A coal blend produced by the Tom’s Creek Preparation Plant in Coeburn, Virginia. This coal is blended to meet contract specifications for the Savannah River Site steam plant operated by South Carolina Electric & Gas, a POC facility repowering candidate. This coal is identified as “Toms Creek coal” in the results sections.

The Toms Creek coal is significantly lower in both sulfur and volatile matter than the Turris coal. In addition, the ash fusion temperature of the Toms Creek coal is much higher, with a calculated T_{250} of 1566°C (2850°F), compared to 1343°C (2450°F) for the Turris coal ash.

Most tests were completed with a burner identified as the “CCV© II”. The CCV©II is a dual register, low-NO_x burner incorporating DB Riley’s proprietary Controlled Combustion Venturi nozzle and spreader, as well as proprietary combustion air diverters.

Additional tests were completed after modifying the CCV©II burner to approximately simulate a first-generation, low-NOx burner design called the WS burner. This burner is currently in use on a number of commercial U-fired boilers. This burner is identified in the results sections as “Baseline” burner, as well as “WS simulation” burner, because it was intended to provide a comparison between the test unit and existing U-fired furnaces in commercial operation .

Burner Type, Stoichiometry

The CCV® II burner performance was significantly different than the “baseline” or WS-type burner. Figure 3 shows the NO_x results for two burner types. NO_x emissions are plotted against burner stoichiometry. In these tests, as burner stoichiometry was reduced, all of the remaining combustion air was added at the first staging level, within the firing chamber, to maintain constant slag tap zone stoichiometry of approximately 1.15.

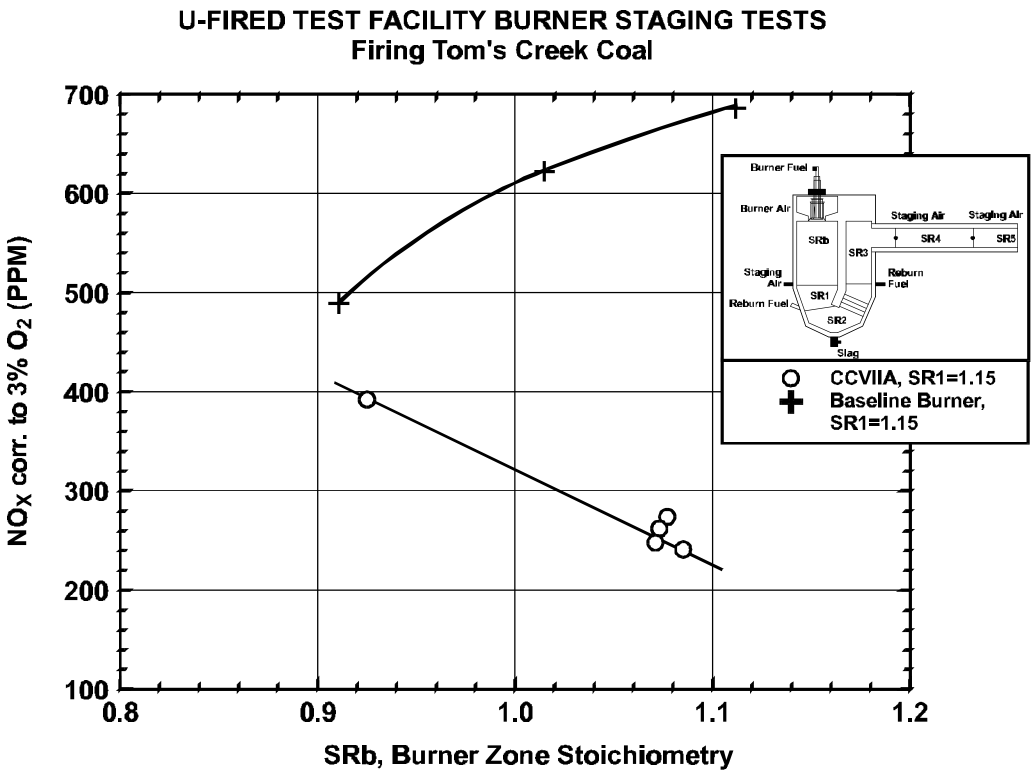

Figure 3. NO_x Versus SRb, Baseline and CCV® Burner

The unstaged CCV® II NOx was remarkably low for slag tap operation. In contrast to typical staging results, NO_x emission from the CCV® II burner increased with decreasing burner stoichiometry. This appears to indicate that staging air at the first level disrupts the well-defined, fuel-rich core of the flame established by the burner. When staging air was injected only downstream of the firing chamber (not shown), NO_x decreased with decreasing burner stoichiometry.

The unstaged baseline burner produced much higher NOx than the CCV® II burner when both were operated unstaged, and the NOx levels decreased with decreasing burner stoichiometry. It is interesting to note that the NOx levels for the baseline burner and the CCV® II low-NOx burner approached the same value as the burners were staged. This result indicated that burner design effects decreased as burner staging increased.

Flame shapes and ash deposition patterns were markedly different for the two burner types. A comparison of video camera images of the CCV® II and the WS-type burner flames is shown in Figure 4. The CCV® II flame has much narrower, well attached flame, resulting in improved low-NO_x performance. The WS-type design produced a wider, detached flame characterized by rapid mixing, high heat release rates, and increased NO_x emissions.

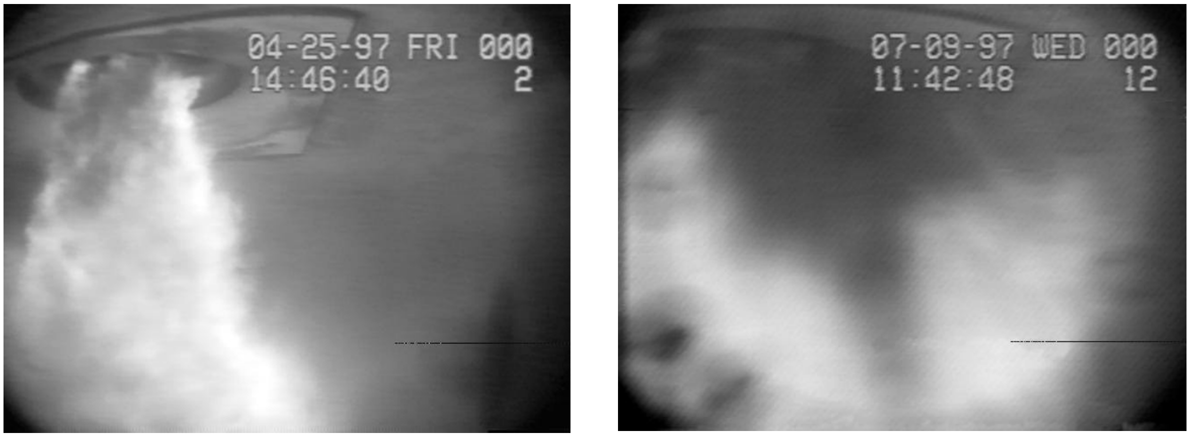

Figure 4. CCV® II (left) and WS-type (right) Flames

Advanced Air Staging and Reburning

Figure 5 is a plot showing the effect of reburning, firing the Turris coal at a constant burner stoichiometry of 1.0. For all reburn tests shown in the figure, pulverized coal was injected upstream of the slag screen to decrease the slag tap zone stoichiometry, and final combustion air was added either near the inlet (open circles), or near the outlet (solid squares) of the horizontal duct. The residence time at the plotted stoichiometry increases from about 1.0 to 1.5 seconds when changing final air addition from the duct inlet to the duct outlet location. A significant reduction of NO_x was effected by reburn fuel injection. This data showed a slight increase in the NO_x when firing at very high fuel reburn rates for slag chamber stoichiometries below 0.9. At a stoichiometry of 0.9, final NO_x was a strong function of reburn zone residence time. At the longer reburn zone residence time, NO_x was reduced to well below the 150 ppm mark, with approximately 10% of the total furnace fuel input injected as reburn fuel.

Figure 5 also includes air staging data (open squares) for a constant burner stoichiometry of 1.0, no reburn fuel, and staging air injected above the slag tap. The air staging data suggest that the NO_x -SR2 relationship holds for either air or fuel addition in this zone. This trend was verified in advanced air staging configurations, where the slag tap stoichiometry SR2 was controlled to 0.9 by staging the burner and delaying air addition until after the slag screen. In these tests (not shown), comparable NO_x values were achieved with air staging alone, and no reburn fuel.

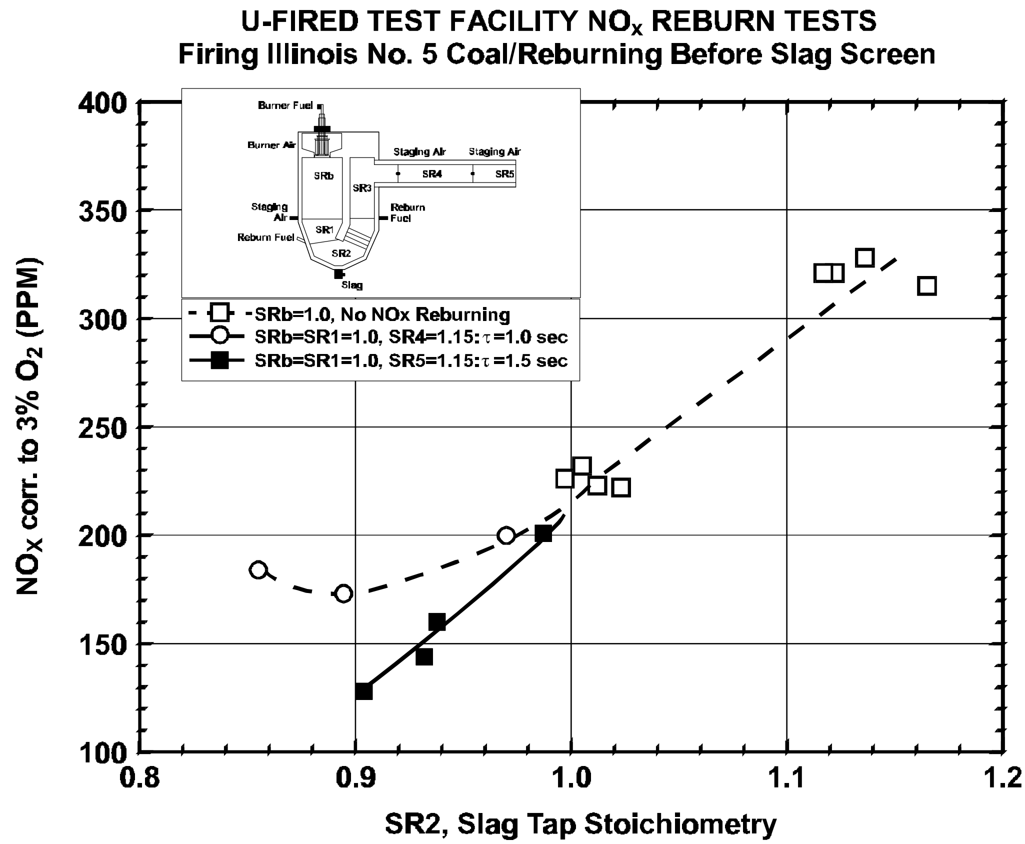

Figure 5. NO_x Versus Stoichiometry, Reburning Tests at 1.0 Burner Stoichiometry

While comparable NO_x control can be achieved with air staging alone, this approach requires that the slag tap zone operate at a nominal 0.9 SR. By using reburning, the reducing zone was moved downstream of the slag tap, allowing the slag tap stoichiometry and reducing zone stoichiometry to be controlled independently. Even though reburn zone residence time was reduced, this is an important advantage, since slag tap stoichiometry affects the temperature and viscosity of the slag, and hence, furnace operability. Final NO_x values of less than 0.2 lb/million Btu were achieved with 10% of the total fuel input injected as reburn fuel after the slag screen, for both Turris and Toms Creek coals.

In Figure 6, the baseline burner NO_x results are compared to results for the CCV® II burner firing the Toms Creek coal at 29 MW_t (100 MBtu/hr). This figure includes the results of unstaged burner operation, as well as burner staging, advanced air staging, and NO_x reburning with both burners. As can be seen, the NO_x reduction methods provided a significant reduction of NO_x levels for the baseline burner. However, NO_x emission goal of 0.2 lb/MBtu was achieved only with the combination of the CCV® II burner and advanced air staging or NO_x reburning.

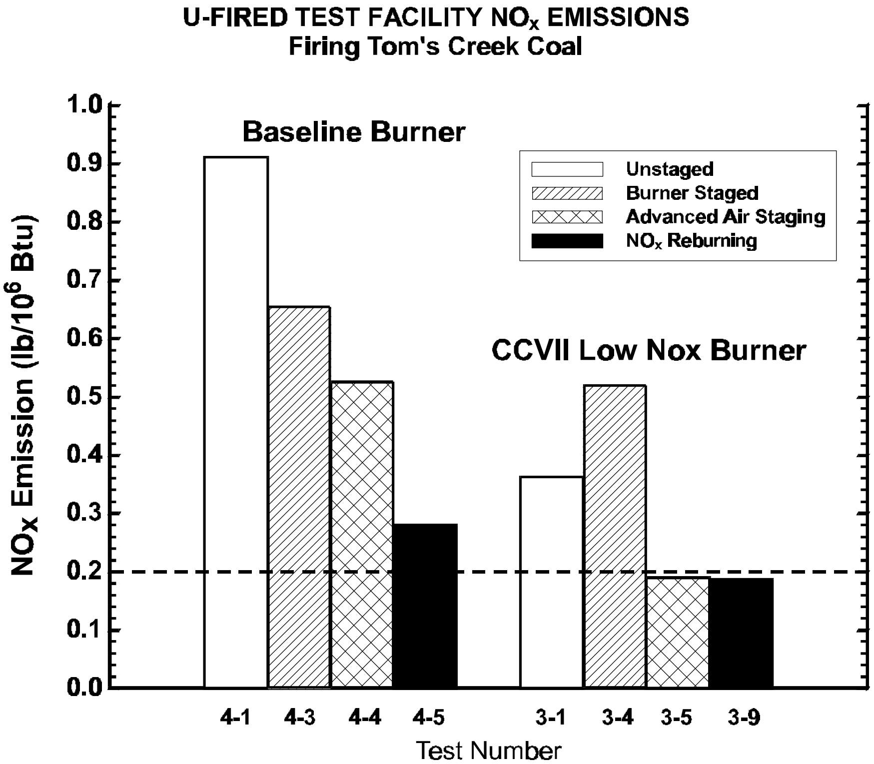

Figure 6. Baseline Burner Versus CCV® II Burner

Combustion Efficiency

The slag and particulate flyash samples were analyzed for carbon content to characterize carbon burnout for the U-fired test furnace. The unburned carbon loss is the amount of heat lost due to unburned carbon, and was calculated from the sample analyses and the slag collection efficiency. While the flyash averaged about 12% carbon, the carbon in the slag was always less than 1%. The ash content of the coals fired was about 10%. Since about 60% of the coal ash was collected as slag, the total unburned carbon loss averaged less than 1%, and never exceeded 2%.

Reburning gave generally lower values of carbon less than air staging for equivalent NO_x levels. Carbon loss was 0.5-1.5% for reburning under low-NO_x operating conditions. Nearly all carbon loss was associated with carbon in the flyash. Therefore, carbon loss would be extremely low in a commercial system with flyash recycle to the firing chamber.

Slag Properties

The slag samples collected from the U-fired test furnace were analyzed to evaluate the physical and chemical characteristics of the material. The material was a glassy granulate. It was dewatered to 15-20% moisture by the drag chain conveyer used to transfer it from the quench water tank to a transfer hopper. The material was dust free, both as discharged and dried.

A Toxicity Characteristic Leaching Procedure (TCLP) analysis was completed for these samples. The results are shown in Table 1.

Table 1. Average TCLP Analysis*

	Firing Coal	Coal Plus Limestone	Detection Limit	1990 RCRA Toxicity Limit
Total Arsenic as As (mg/L)	BDL	BDL	0.20	5
Total Barium as Ba (mg/L)	1.07	0.88	0.05	100
Total Cadmium as Cd (mg/L)	BDL	BDL	0.05	1
Total Chromium as Cr (mg/L)	BDL	BDL	0.05	5
Total Lead as Pb (mg/L)	0.29	0.17	0.10	5
Total Mercury as Hg (mg/L)	BDL	BDL	0.001	0.2
Total Selenium as Se (mg/L)	BDL	BDL	0.20	1
Total Silver as Ag (mg/L)	BDL	BDL	0.05	5

* UFTF slag samples. Average of 3 each with and without limestone firing Turris coal.

Comparison With Commercial U-Fired Units

The objective of reducing NO_x levels to less than 0.2 lbs/MBtu was achieved using the CCV® II burner, configured with either coal reburning or with advanced air staging. This is an extremely low value for a slag tap system. A key question was whether the test facility correctly simulates the NO_x performance which can be achieved in a full scale boiler.

The advanced slag-tap firing system developed in this project is based on a single firing plane, high-capacity steam generator design constructed in the early 1970's. These units were equipped with single-register, swirl-stabilized, high-velocity burners called "W", or whirl-burners. Additional boilers were constructed in 1981-1982, and were equipped with a first-generation, low-NO_x burner developed for NO_x control in wall fired boilers. This burner, the "WS" or whirl-staged-burner, features dual air registers, but differs significantly from current low-NO_x burners represented by the Deutsche-Babcock DS burner or the DB Riley CCV® II.

Previous sections described tests performed after modifying the burner to approximately simulate the WS burner, a first-generation, low-NO_x burner in commercial service in a number of U-fired boilers. In this section, the NO_x emissions measured in the UFTF are compared to values observed in "Field Unit A" equipped with the WS burner, or "Field Unit B", equipped with the W-burner.

NO_x vs. Burner Stoichiometry. Figure 7 shows the effect of reduced burner stoichiometry (SRb) with two different approaches to air staging in the W-burner equipped Field Unit B. In the Retrofit I configuration, staging air was admitted through ports in the firing roof, outboard of, and parallel to, the burners. In the Retrofit II configuration, staging air was admitted through the firing chamber walls, downstream of, and perpendicular to, the burners, to maintain a firing chamber stoichiometry of approximately one. Final combustion air was added through the walls downstream of the slag screen.

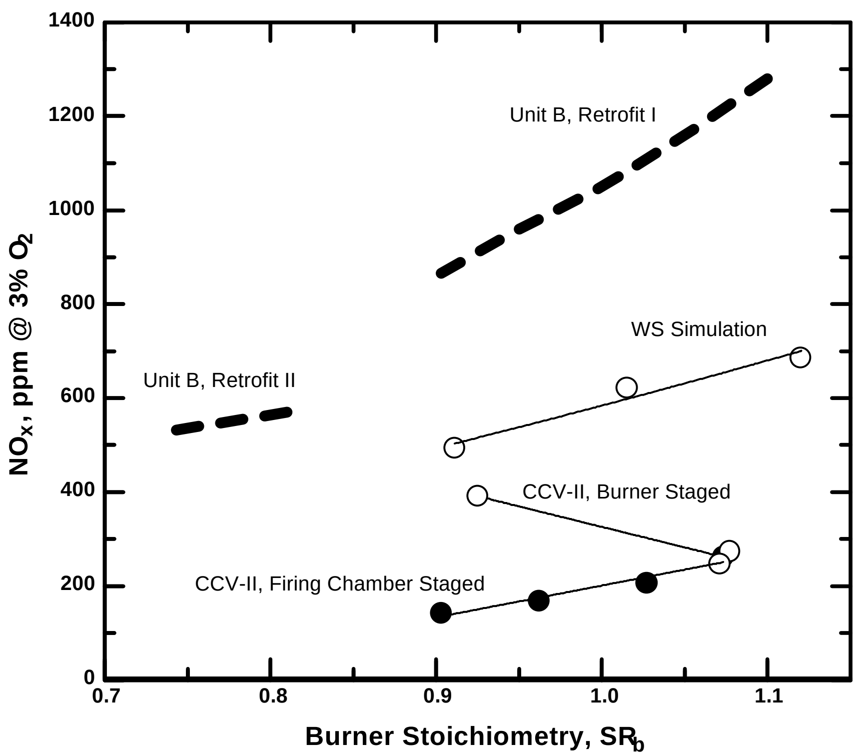

Figure 7. NO_x Versus SRb for Field Unit B and Test Facility

Also shown in Figure 7 are the results of the UFTF tests with the simulated WS burner. Unstaged NO_x is approximately one-half that of Unit B, (consistent with the lower unstaged NO_x in the WS-equipped Unit A). However, the slope of NO_x vs. SRb is similar to that of either Retrofit I or II. Furthermore, while there is not a common SRb for direct comparison of UFTF results to Retrofit II, the absolute NO_x levels for the UFTF WS simulation extrapolate to approximately the same absolute values as Retrofit II at reduced SRb. Staging air for the tests shown was admitted through the firing chamber sidewalls, similar to Retrofit II. The NOx emissions for the CCV® II are shown for comparison.

<u>NO_x vs. Surface Area Heat Release</u>. NO_x data are available for Field Unit A over the range of 50% to 100% boiler load, and are plotted in Figure 8 as a function of surface area heat release rate. Uncontrolled NO_x at half-load decreases approximately 20% to 630 ppm, from the full-load value of 780 ppm. At low load, the Unit A heat release rate is equivalent to that of the UFTF, which is 0.33 MW_t/m^2 at nominal design load. As shown in the figure, the absolute value of unstaged NO_x measured in the UFTF with the WS burner simulation is 690 ppm, about 10% higher than the Field Unit value at the same heat release rate.

Flue gas recirculation to the burners in Unit A, when maintained at a constant percentage, reduced NO_x by about 23% across the load range. There were no directly comparable tests of FGR in the test facility. However, burner staging with in-chamber air addition may be compared qualitatively as a moderate NOx reduction approach. This technique applied to the simulated WS burner in the UFTF reduced NO_x 10-30%.

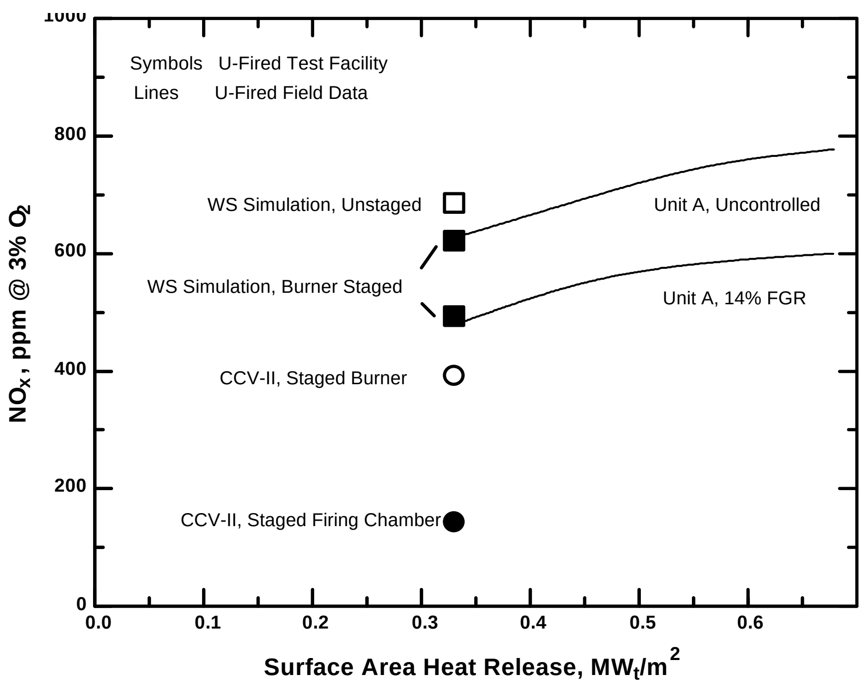

Figure 8. NO_x Versus Heat Release for Field Unit A and Test Facility

Finally, the range of NO_x results achieved with the CCV® II burner is illustrated in the figure for comparison. The highest NO_x value from the CCV® II represents a reduction of 40% in comparison to either Unit A (at a common heat release rate, without FGR), or to the simulated WS burner in the test facility. The lowest NO_x value achieved with the CCV® II burner represents a reduction of 80% from either of these comparison points.

We conclude that the test facility provides a valid simulation of the effectiveness of NO_x control measures applied to a U-fired boiler. Under low-NO_x conditions in the test facility, there was no observed influence of load on NO_x over the narrow range of heat release (about 0.30 to 0.33 MW_t/m^2) tested. The data from Unit A indicate that, at most, a 20% adjustment to absolute NO_x values may be required for a factor of two increase in surface area heat release.

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